551.515 (729.2)   # SECTION II.—GENERAL METEOROLOGY.

WEST INDIES HURRICANES AS OBSERVED IN JAMAICA.

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CONTENTS.

INTRODUCTION.

If we look at a chart of the West Indies it is evident that the chain of small islands which form the eastern boundary of the Caribbean Sea can give warning westward of these storms which, generating to the east of those islands, pass westward over them; but that the islands themselves will always have to depend chiefly on their own local observations.

Again, the larger islands from Porto Rico to Cuba should be continually on the watch for the possible curving northward of any storm which may be passing along the Caribbean Sea; and this applies more particularly to Jamaica; such a storm advancing from the Windward Islands may affect Jamaica in several ways, or by passing far north or far south it may hardly affect that island at all.

It thus appears that there is need for local observations to supplement the telegraphic warnings issued by the United States Weather Bureau at Washington, and it was with this object that the following pages were written.

Again, the local telegraph wires soon go down as the storm advances, hence it is advisable to consider the observer as isolated with regard to information from a distance, whether or not he has received the general warning from Washington.

Technicalities can not be avoided, but I have done my best to make the matter as simple as possible, so that any one who has a good barometer and a fair knowledge of clouds may be able to forecast for his immediate locality, and to make valuable observations for the future development of the cyclonic theory. And I may as well begin by quoting from the notice published in Jamaica at the commencement of each hurricane season:

A barometric "depression" over a large area involves weather "disturbance"; the low barometer is always accompanied by rain, sometimes by very heavy rain; and if the depression does not speedily fill up and disappear, the wind begins to circulate about its center in a direction contrary to that of the hands of a watch face upward on a table.

When this action is continued the barometer gradually falls at the center, the wind sweeps faster round the center, and the system thus established is called a "cyclone". It is to the position and motion of the centers of these "depressions" and "cyclones" that the telegraphic storm warnings refer.

When a cyclone is fully developed, the wind near the calm center moves round it with "hurricane" force; so that when it is reported that a "hurricane" swept a certain island, we know that the center of a great cyclone passed over or near that island.

And with this understanding we shall continue to use the word "hurricane", which history has made applicable to a great storm in the West Indies in the same way that the word "typhoon" is applicable to a similar storm of the China seas.

GENERAL DESCRIPTION OF CYCLONES.

In the year 1886 the late Hon. Ralph Abercromby visited the observatories at Mauritius, Madras, Calcutta, Manila, Hongkong, and Tokyo, to collect information respecting tropical cyclones, and he published the results in an article "On the relation between tropical and extra-tropical cyclones."[1] It was read before the Royal Society in February, 1887, but the pamphlet he sent me contains additions up to June of that year where reference is made to the work of the late Padre Viñes at Habana. The conclusions at which he arrived are so clearly expressed and unbiased, that I can not do better than quote them in paragraphs, adding notes taken for the most part from my own observations made in Jamaica during the past 40 years.

(1) *All cyclones have a tendency to assume an oval form; the larger diameter may be in any direction, but has a decided tendency to range itself nearly in a line with the direction of propagation.*
The center of the cyclone is almost invariably toward one or other end of the longer diameter; but the displacement may vary during the course of the same depression (op. cit., p. 28).

The "oval form" is of course that of the isobars or lines of equal barometric pressure surrounding the center; but the cyclones passing over or near Jamaica in recent years have been so nearly circular that in the case of an advancing storm we can assume that the isobars are fairly circular, and lay off the direction of the center by the direction of the wind and cloud-drift in accordance with the results given in sections (11) and (13).

[1] Proceedings of the Royal Society, London, Nov. 1887, vol. 43, pp. 1–30.

FIG. 1.—Kempshot Observatory, Jamaica, B. W. I., altitude, 1,773 feet above sea-level; with commanding view in all directions.
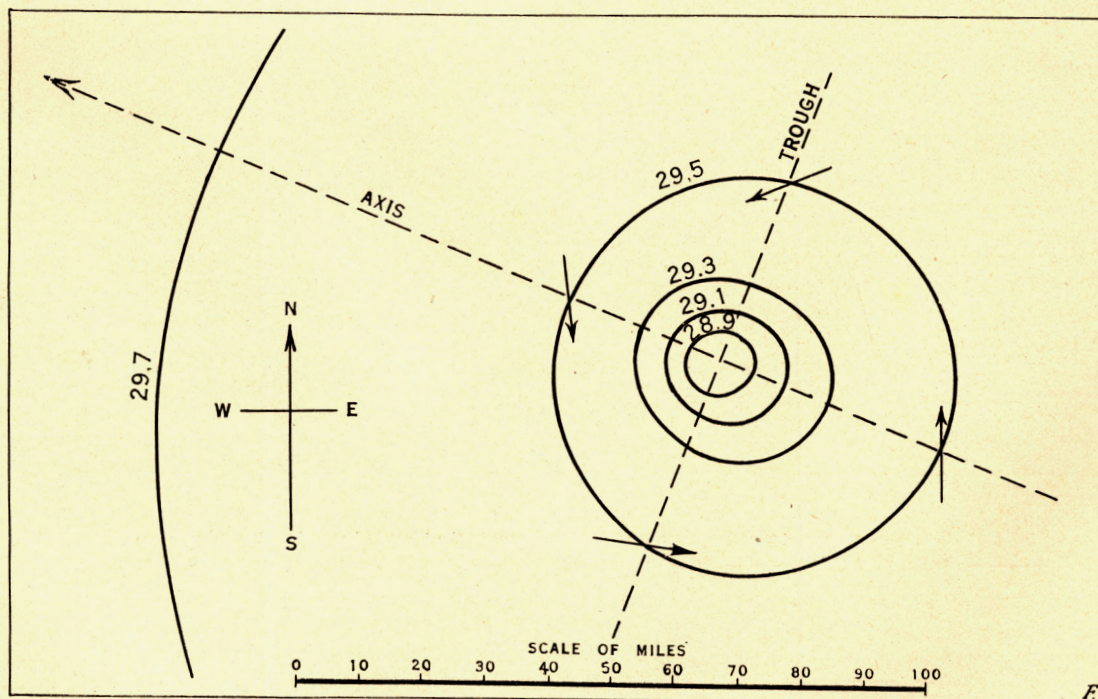
FIG. 2.—Distribution of pressure and close-in winds in an average hurricane moving west-northwestward.
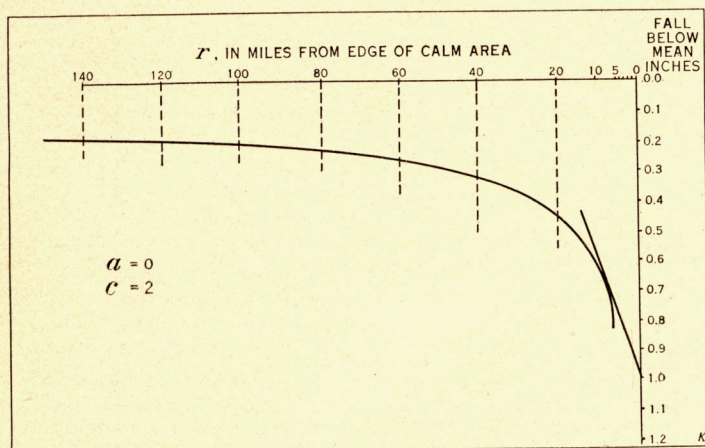
FIG. 3.—Relation of fall of pressure below the mean and the distance from the edge of the central calm. (See equation 1.)
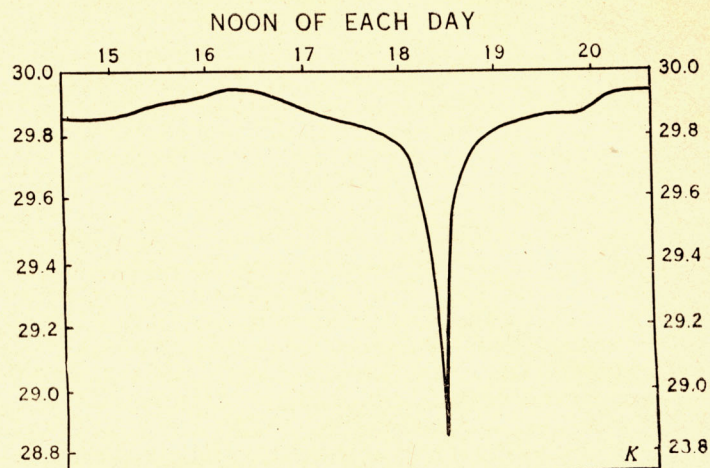
FIG. 5.—Barogram at Kingston for August 15–20, 1880, showing the rise two days before the hurricane of 1880, August 18, while the center was still 800–900 miles east of there.
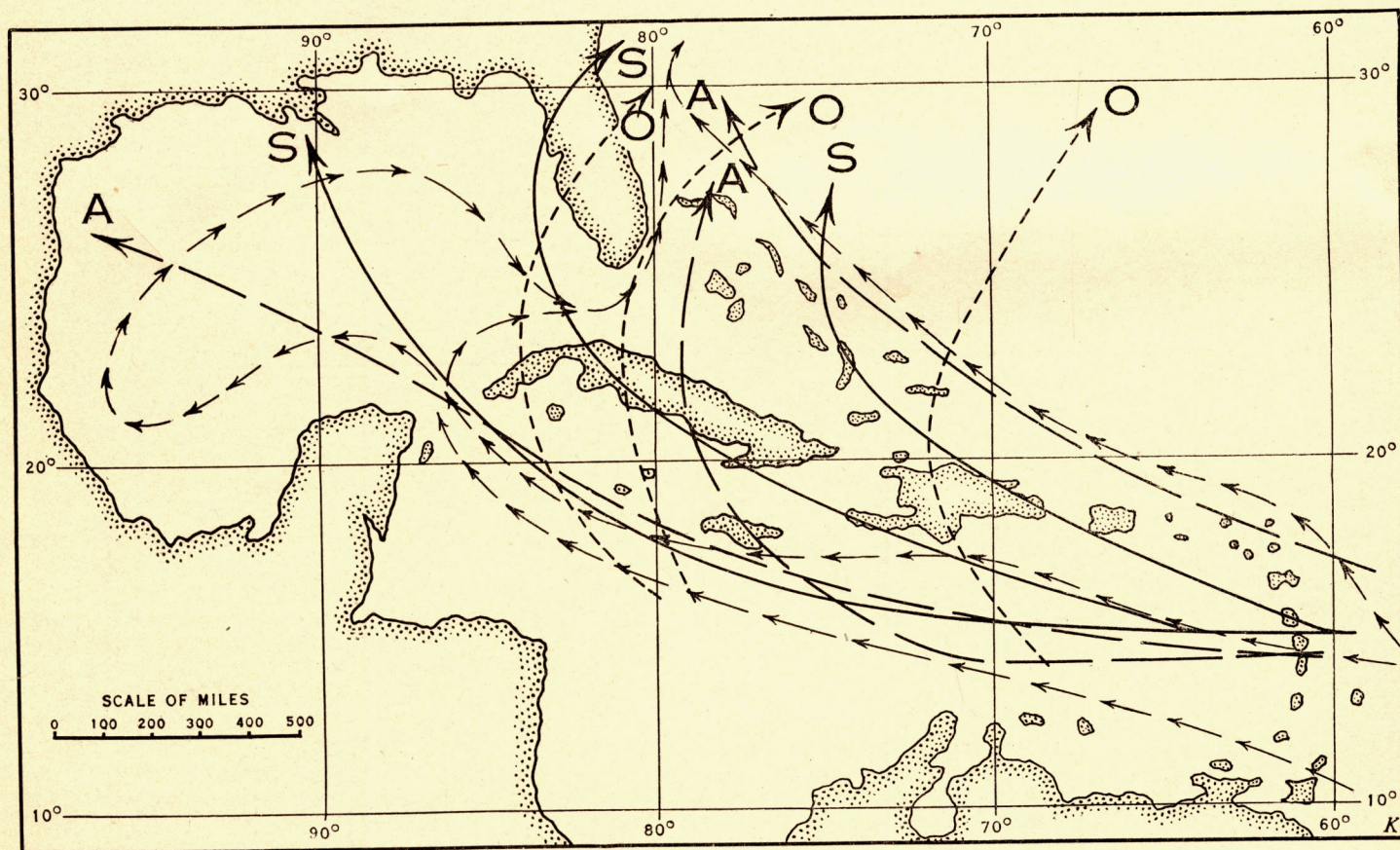
FIG. 4.—Ocean currents and average tracks of hurricanes in the West Indies and Gulf waters.

— — — — A=August tracks; — — — — S=September tracks; - - - - - - O=October tracks; →→→ Ocean currents.

In the case of the hurricane, 1915, August 12 and 13, special means were adopted in W. R. No. 446 [2] to show that the isobars were circular; and similarly for the hurricane, 1916, August 15 and 16, in W. R. No. 460.

This circularity is no doubt due to the fact mentioned in the next paragraph; and it explains the absence of "trough" phenomena described in section (17).

Figure 2 represents the slightly oval isobars of an average cyclone moving toward the west-northwest along its axis, having the gradients steeper in front than in the rear, as was the case in the hurricane of 1903, August 11. The barometric pressure of each isobar is marked, the pressure in the calm central area being 28.9, or an inch below the mean; and the four small arrows show the direction of the wind at different points in accordance with with the results for small distances given in section (11). The trough or dividing line between falling and rising pressures as the cyclone moves forward, is in this case at right angles to the axis.

We shall measure gradients in decimals of an inch [barometric] per mile; and it will be found that between the isobars 29.7 and 29.5, the average gradient is only 0.003, while the gradient between 29.1 and the center is 0.05 inch.

Consequently while the fall is small when the center is 100 miles or so distant, and while it continues to fall very slowly at a place in its direction of motion, nearer the center the fall is very rapid and the "hurricane" rushes forward, as it were.

As this is all very important, figure 3 shows in another form the connection between pressure, or rather the fall of pressure below the mean, and the distance r from the edge of the calm area.

The curve in figure 3 may be taken to be the average of a large number of cyclones; and it represents the algebraic equation

$$\Delta p = \frac{c}{\sqrt{r-a}},\tag{1}$$

where Δp is the fall of pressure, corrected for diurnal variation, below the mean for the time of the year in question, and where c and a are constants for the same cyclone, with limitations, of course, as to front and rear and to time. The constant c may vary between 1 and 4 inches; and a may be as much as ± 18 miles. In figure 2, c has been taken to be 2, which often occurs, and a has been taken to be the zero.

When a is large and positive the gradient near the center is very steep; this often occurs among the small islands east of the Caribbean Sea; when a is large and negative, the gradient is small, and apparently the cyclone is either commencing or dying out.

It will be noticed in figure 2 that at a certain point the fall of pressure leaves the curve and follows the tangent to the lowest reading at the edge of the calm central area; and if a and c are known, and also the lowest pressure in the central area, it is very easy to draw the final tangent; but it is not so easy to find the exact point where the tangent touches the curve.

Let G be the gradient at any point in the curve measured in decimals of an inch of mercury per mile of the radius r; then by differentiating equation (1), or by a similar algebraic process (see Note A), we get

$$G = \frac{dp}{dr} = \frac{\Delta p}{2(r-a)},\tag{2}$$

Let Δp_0 be the fall at the center, let p_1 be the fall at the point where the tangent takes off, and let r_1 be the radius of this point or its distance from the calm central area: then

$$G = \frac{\Delta p_1}{2(r_1 - a)} = \frac{\Delta p_0 - \Delta p_1}{r_1},$$

whence we easily obtain (see Note B),

$$\Delta p_1 = \tfrac{2}{3}\Delta p_0 - \tfrac{1}{3}a/c^2\Delta p_1{}^3,\tag{3}$$

When a is zero, $\Delta p_1 = \tfrac{2}{3}\Delta p_0$; when a is a positive or negative quantity, equation (3) is a cubic, but it may easily be solved by approximation. And then r_1 may be found from the curve, or from equation (1), and G from (2).

These equations should not be pressed as though the cyclone functions exactly followed the law expressed by equation (1); they are rather intended to give a clear idea of what we may expect from a general average.

(2) *Tropical hurricanes are usually of much smaller dimensions than extra-tropical cyclones; but the central depression is much steeper and more pronounced in the former than in the latter.*

In the hurricane of 1903, August 11, the center passed along the middle of Jamaica, and the diameter of the storm area where the wind was above 50 or 60 miles an hour, was only 40 miles;[3] and outside a diameter of 100 miles the wind was not more than 20 miles an hour. But near the center the gradient was 0.04 inch per mile, and the wind reached hurricane force in gusts. And similarly for all our cyclones.

In the Windward and Leeward Islands the gradients near the centers are often much steeper, as already said, and the wind terrific; but the storm area is no larger.

(3) *Tropical cyclones have less tendency to split into two, or to develop secondaries than those in higher latitudes.*

When a cyclone develops, a minor depression is generally formed, which confuses the indications; the [minor] depression may move along the mid-Caribbean while the cyclone may either follow it or move northwestward; or a true secondary may be formed on the edge of the primary.[4]

(4) *A typhoon, which has come from the Tropics, can combine with a cyclone that has been formed outside the Tropics, and form a single new, and perhaps more intense, depression.*

(5) *No cyclone is an isolated phenomenon; it is always related to the general distribution of pressure in the latitudes where it is generated. The concentric circles, which are usually drawn to represent a cyclone, ignore the fact that a cyclone is always connected with and controlled by some adjacent area of high pressure.*

Of greater importance than the isobars are the curved lines, on a chart, showing the tracks of centers. Charts have been drawn showing on a single sheet the courses of a large number of West Indies hurricanes for each of the three "hurricane" months of August, September, and October, without reference to the particular pressure conditions which may affect each hurricane; and it is difficult to make out any average track or any rule affecting them.[5]

If, however, in Prof. Fassig's charts we attempt to group the tracks which pass south of Haiti (Hispaniola)

[3] In the U. S. MONTHLY WEATHER REVIEW for September, 1905, there are charts and a general description of this hurricane, sent to the REVIEW by the writer as the Jamaica Weather Service was closed between 1899 and 1907.
[4] As in the hurricanes of 1915, Aug. 12, and 1916, Aug. 15.
[5] "West Indian Hurricanes," Prof. E. B. Garriott; and "Hurricanes of the West Indies," Prof. O. L. Fassig, both published by the U. S. Weather Bureau, Washington.

and Cuba, those which pass for the most part north of those islands, and those which are intermediate, or which curve from the first group into the second, we obtain the following remarkable chart, figure 4, where the average tracks for the three groups in August, September, and October, are distinguished by the initials A, S, and O.

Importance must be attached to the place of commencement of each of these average curves, but none to the place where the arrowheads are marked to show the direction of motion—the curves may be continued northeastward to any extent.

There is a great deal in this chart to attract attention; most of the cyclones begin in about latitude 15°, where the rotational effect of the earth on moving currents is sufficient to set up cyclonic rotation; and most of them begin a few miles east of the Lesser Antilles where the great equatorial oceanic current is split in two, one part going into the Gulf of Mexico and the other part skirting the Bahama Islands.

Indeed the general effect of currents can not be overlooked; in figure 4 only the principal currents given by Lieut. Soley [6] have been marked down; and it will be noticed that the southern August and September tracks pass between the lower north and the south equatorial currents straight into the Gulf; that the intermediate August track commences similarly but curves toward the currents east of Florida; that the intermediate and northern September tracks lie between the two northerly equatorial currents; and that the northern August track simply follows the northernmost equatorial current past the Bahama Islands.

In October the pressure is generally high in the Southern States of North America; and the three October tracks apparently avoid the high pressure by curving sharply to the right.

Cyclones require vapor, which they turn into rain, thereby developing the heat necessary for their prolonged existence; and it seems probable that the supply is insufficient until the month of August, when the region of equatorial heavy rains between South America and Africa reaches as far north as latitude 15°. [7]

(6) *In all latitudes pressure often rises over a district just before the advent of a cyclone. The nature of this rise is at present obscure; but the character of the unusually fine weather under the high pressure is identical both within and without the Tropics.*

Figure 5 shows the rise in pressure at Kingston, Jamaica, two days before the hurricane of 1880, August 18, when the center was 800 or 900 miles away to the east; the mean height of the barometer was 29.9 inches at that time of the year; and the rise in pressure was 0.08 inch. Both the 16th and 17th were fine and calm in Kingston.

But the change in the weather is much more strongly marked in the interior parts of the island; during the autumnal months daily thunderstorms occur; the mornings are fine; clouds of the cumulus type gather and ascend in large masses, and break up with rain and much lightning. Consequently when it is found that there is no ascensional movement, that the sky remains almost clear, and that what clouds there may be apparently descend and dissolve, the unusual weather at once attracts attention.

(7) *In all latitudes a cyclone which has been generated at sea appears to have a reluctance to traverse a land area, and usually breaks up when it crosses a coast line.*

In figure 4 cyclones following the southern August track generally break up on reaching the coast of Mexico; cyclones following the middle September track are sometimes broken up by Haiti or Cuba; but a small island like Jamaica has no such effect. [8]

(8) *After the passage of a cyclone in any part of the world there is a remarkable tendency for another to follow very soon, almost along the same track.*

With reference to both the southern August and September tracks, it often happens that a small cyclone precedes a large and dangerous one; the last of the more noticeable occasions was 1915, September 24, as reported in W. R. No. 447. This tendency for a "secondary" to precede the primary, both taking the same course south of Jamaica, greatly confuses the indications as already stated in section (3).

(9) *The velocity of propagation of tropical cyclones is always small, and the average greatly less than that of European depressions.*

The centers of the cyclones of 1903, 1915, and 1916, all moved with a velocity of about 20 miles an hour; but as a rule the velocity is less, especially when the cyclones are generating. A number have generated south or southwest of Jamaica, when the centers appear to be stationary or rather to oscillate a little east and west before they move on their course with increased energy.

(10) *There is much less difference in the temperature and humidity before and after a tropical cyclone than in higher latitudes. The quality of the heat in front is always distressing in every part of the world.*

The temperature of the air during a hurricane at night is 5 or 6 degrees (F.) above the average (W. R. No. 446, p. 7); and the oppressive heat is at least disagreeable. [9]

(11) *The wind rotates counter-clockwise round every cyclone in the Northern Hemisphere; and everywhere as an in-going spiral. The amount of in-curvature for the same quadrant may vary during the course of the same cyclone; but in most tropical hurricanes the in-curvature is least in front and greatest in rear, whereas in England the greatest in-curvature is usually found in the right front. Some observers think that, broadly speaking, the in-curvature of the wind decreases as we recede from the Equator.*

In order to make a general study of the direction of wind and cloud drift with reference to the center of a cyclone, it will be necessary to adopt some simple system such as the following: At the place of observation D in figure 6 draw the wind-arrow or cloud arrow, the arrows being of course supposed to fly with the wind or cloud; and measuring angles from the east point of the horizon round by the north, call the wind angle a. Again at the place of observation lay off the direction of the center, and measuring the same way, call the angle β. Then if $\phi = \beta - a$, ϕ is the angle between the center and the wind arrow.

[6] "The circulation in the North and South Atlantic Oceans"—supplement to the Pilot Charts—by Lieut. J. C. Soley, U. S. N., February, 1916.
[7] This theory of the mechanism of hurricanes is still the subject of discussion.—c. a., jr.

[8] In the hurricane of 1903, Aug. 11, the central area passed over Vale Royal near Kingston, and along the rough interior of the island to Montego Bay. These places are 85 miles apart, but the lowest barometers were exactly the same at both places, namely, 28.93 inches; and there was the same estimated velocity of the wind.
[9] I have been unfortunate with thermometer screens during hurricanes. I have them clamped to wooden stands firmly attached to the ground; but something has to give way, and the thermometers are either displaced or broken.

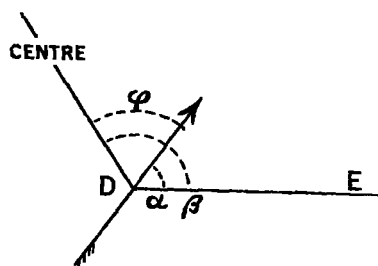The following diagram and table will be useful:

FIG. 6.—Diagram illustrating system of naming angles for the wind-arrow at the station D.

Wind or cloud drift.

From—	α	From—	α
	°		°
n.	270	s.	90
nnw.	292	sse.	112
nw.	315	se.	135
wnw.	338	ese.	158
w.	0	e.	180
wsw.	22	ene.	202
sw.	45	ne.	225
ssw.	68	nne.	248
s.	90	n.	270

Similarly for cloud drift:

> For stratus, $\phi_1 = \beta - \alpha_1$.
> For cumulus, $\phi_2 = \beta - \alpha_2$.
> For cirrus, $\phi_3 = \beta - \alpha_3$.

The length of the arrow, or the number of feathers, may be arranged to indicate the velocity of the wind according to Beaufort's scale.

Now the average course of the center of cyclones in the West Indies between longitudes 60° and 75° is from east-southeast to west-northwest (see fig. 4); and the observations of the wind in Jamaica were divided among the following quadrants:

1. ese, and β between 300° and 29°.
2. nne, and β between 30° and 119°.
3. wnw, and β between 120° and 209°.
4. ssw, and β between 210° and 299°.

Moreover the observations were further divided into two groups according to distance, the first group containing those made when the center was at a considerable distance, say 300 or 400 miles, and the second group containing those made when the distance was small and less than 100 miles.

But over the Caribbean Sea there is a constant drift which blows over Jamaica from the east-southeast during the hurricane months of August, September, and October; and although on the plains it is subject to the irregularity of the sea- and land-breezes, yet at higher elevations it is much more regular; and for the general reduction of observations it was assumed that the constant drift flows at the rate of 8 miles an hour.

In figure 7 let D be the place of observation, and DE a line drawn toward the east point of the horizon: then if DA be the drift from east-southeast, and DB the observed wind from northeast at 10 miles an hour, by joining AB and completing the parallelogram we find that the cyclonic wind, or wind due to the cyclone alone, is DC or a wind from north at $10\frac{1}{2}$ miles an hour.

The observations were taken from 13 of the more suitable cyclones which were apparently unaffected by secondaries, or other cyclones at a distance; they were formed into groups, and the general drift was eliminated
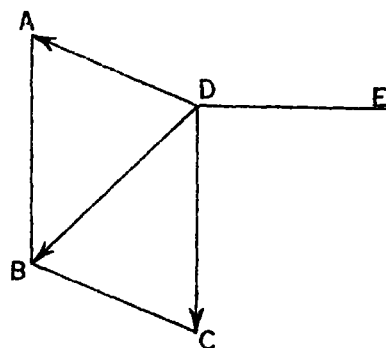

FIG. 7.—Parallelogram of wind-velocities at the station D.

from the groups by means of the parallelogram of velocities. The results are given in the following table:

Quadrant, or bearing of center.	Angle ϕ between wind arrows and center.		
	Distance large.	Distance small.	Average distance.
	°	°	°
(1) ese.	44	62	53
(2) nne.	72	77	74
(3) wnw.	44	68	56
(4) ssw.	36	47	41
Means.	49	64	56

The first thing that we notice is that the angle is larger when the distance is small; that is to say, the motion becomes more circular as we approach the center.

The next thing we notice is that while the angles in quadrants (1) and (3) of the table are equal, or nearly so, the angle is a maximum in (2) and a minimum in (4). The rule here seems to be that when the center is approaching in (1), or receding in (3), the angle is about the same, namely, 44° for large distances, and 65° for small. But when the center is passing in (2), the wind arrow lags behind the moving center; and when the center is passing in (4), the wind arrow lags in front, so that the angle is too large in (2), and too small in (4). The wind arrows for small distances are marked in figure 2.

Now a large number of cyclones pass to the northwest of the British Isles on a northeasterly course, so that "the greatest incurvature on the right front" in England corresponds with wind arrow in Jamaica lagging in front of the moving center (4). And as 49° is the average angle for large distances, the in-curvature is 41° in Jamaica, while it is only about 20° for the cyclones farther north [10] so that the in-curvature "decreases as we recede from the Equator."

For some details respecting these important conclusions reference must be made to the Quarterly Journal of the Royal Meteorological Society for July, 1916, and January, 1917, but even there the voluminous observations had to be summarized.

(12) *The velocity of the wind always increases as we approach the central calm in a tropical cyclone; whereas in higher latitudes the strongest winds and the steepest gradients are often some way from the center. The portion of a cyclone which is of hurricane violence forms, as it were, a kernel in the center of a ring of ordinarily bad weather. In this peculiarity tropical cyclones approximate more to the type of a whirlwind tornado, but the author does not think*

[10] *Great Britain. Meteorological Office.* "Barometer Manual (Official)," 1912, p. 30. London. Wyman & Sons.

that a cyclone is only a highly developed whirlwind, as there are no transitional forms of rotating air.

The first part of this paragraph is perfectly true, but I do not understand the middle part. The wind increases as we approach the central calm, which may be a few miles or as much as 38 miles in diameter, so that a ring of wind of hurricane force surrounds the calm center; the diameter of the storm area may be 100 miles or so, and the diameter of the area under cyclonic influence may be 1,800 miles or more. And as cyclones commence by rotation of the wind over large areas, there is nothing to connect them with tornadoes, whose diameters may not exceed 100 or 200 yards.
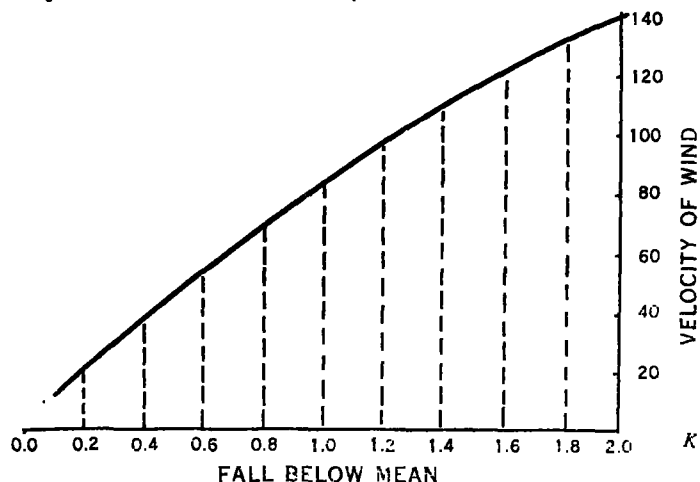

Fig. 8.—Curve expressing relation between the fall of the pressure below the mean and the velocity of the wind

There is a close connection between the velocity of the wind and the fall of pressure. Let v be the velocity in miles per hour corrected for the constant east-southeast drift as explained in section (11); let Δp be the fall of pressure below the mean for the time of year and hour of the day, as before; then

$$v = 98\Delta p - 48\Delta p^2, \qquad (4)$$

In the table below the first 5 results of observation were given by the same researches which gave the angle between the direction of the center and the wind arrow; the sixth was taken from observations in Jamaica given below on page 583; and the last result was taken from the observations at New Orleans during the hurricane of 1915, September 29, which passed south of Jamaica and apparently developed as it crossed the Gulf of Mexico.[11]

Δp.	Velocity in miles per hour.		Remarks.
	Observed.	Computed.	
Inches			
0.10	10	10	
0.22	20	21	
0.45	41	41	See table. p. 581.
0.56	52	50	
0.70	55	62	
1.04	83	87	Observations in Jamaica.
1.80	130	131	New Orleans, Sept. 29, 1915.

All these velocities assume that the wind blows steadily, and is registered by a Robinson anemometer during a considerable interval of time; but the wind in a cyclone

11 U. S. Monthly Weather Review, September, 1915, 43:472.

blows in gusts, as described in section (15); for velocities of 20 and 30 miles an hour the gusts are often twice these figures; for velocities of 50 and 60 miles an hour the gusts are about $1\frac{1}{2}$ times these figures; and they become appalling as the center draws near.

The wind increases in velocity as we approach the central area, according to the rule above or to some modification of it, and finally the velocity is such that the hydrodynamic equation is satisfied, and the "centrifugal force"[12] of the rotating air is equal to the pressure toward the center produced by the gradient, and this determines the radius of the calm area, r_0.

Taking the well-known equation

$$p = k\rho(1 + 0.003665t)$$

where p and ρ are the pressure and density of the air, and t its temperature centigrade, if we take $t = 29°$ at the center, and if we take miles and hours as the units of space and time, $k = 392,200$ (see Note C) and the equation becomes

$$p = 433,900\rho.$$

We thus have, supposing the center to be at rest,

$$\frac{v^2 \sin^2 \phi}{r_0} \rho = \frac{dp}{dr} = G,$$

or

$$v^2 = 433,900 \frac{Gr_0}{p \sin^2 \phi}. \qquad (5)$$

We have only two good cases to test this equation; when the central area passed over Brandon Hill, 1903, August 11, and when the central area passed over Negril Point Lighthouse, 1916, August 15–16.

BRANDON HILL, AUGUST 11, 1903.[13]

Immergence.	*Emergence.*
9 a. m.	10 a. m.
r_0, 8 mis	8 mis.
G, (8:45ᵃ–9:15ᵃ) 0.040 in	(9:42ᵃ–10:15ᵃ) 0.025 in.
p, 29.2 in	29.2 in.
α, 248°	90°
ϕ, 90	70
v, 70 obs., 69 comp.	60 obs., 58 comp.

NEGRIL POINT LIGHTHOUSE, AUGUST 15–16, 1916.[14]

15th, 10:30 p. m.	16th, 1:30 a. m.
r_0, 19 mis	19 mis.
G, (10ᵖ–11ᵖ) 0.008 in	(1ᵃ–2ᵃ) 0.013 in.
p, 29.1 in	29.2 in.
α, 292°	135°
ϕ, 50	26
v, 60 obs., 62 comp.	96–120 obs., 140 comp.

The last computed velocity is too large; but if ϕ had been taken to be 34° instead of 26°, the computed velocity would have agreed with the observed velocity, which was about 108 miles/hr. The difference is due to an irregularity in the wind, which at first blew too nearly toward the center. Such irregularities will always occur, and these computations may be considered satisfactory.

If instead of taking two special cases we had taken all the observations of velocity near the calm area, which are here given, the mean velocity of 83 miles nearly agrees with the velocity computed by equation (4).

12 The Editor prefers the more accurate expression "centrifugal tendency."
14 Monthly Weather Review, September, 1905.
13 Jamaica Weather Report No. 460.

Date.	Station.	p.	v.
		Ins.	*Mis./hr.*
1880, August 18	Kingston	28.85	80
1903, August 11	Vale Royal	28.93	70
1903, August 11	Brandon Hill	28.93	60–70
1912, November 18	Kempshot	29.02	80–120
1912, November 18	Negril Point	28.49	80–120
1916, August 16	Negril Point	29.07	60–96 or 120
Means		28.88	83

And as the average pressure was 29.92 [inches] for these dates, we have $\Delta p = 1.04$, and $v = 87$ from (4), which are well within the probable error of observation.

But taking the observed value from (5) we have $Gr_0 = \frac{1}{2}\sin^2\phi$, which gives a general idea of the relation between G, r and ϕ, at the edge of the central calm. When $\sin\phi$ is 1, or otherwise constant, the smaller the radius of the calm area the larger the gradient, and vice versa. Such small areas and large gradients often occur among commencing cyclones to the east of the Caribbean Sea; and for an example of a large area and small gradient we can refer to the Jamaica hurricane of 1916, August 15–16.

Now, while $v\sin\phi$ is the velocity of the air rotating in a circle round the center, $v\cos\phi$ is the velocity of the air pouring into the calm area from all sides. The air here is hot and dry, as described in section (16). Its high temperature will cause it to ascend and to partly dissolve the clouds, so that in the daytime patches of blue sky may be seen between them, forming what is called the "bull's-eye". Constant action is hereby maintained, more air is drawn in, more vapor condensed into rain, more heat developed. In fact, a "machine" is established, which finds fresh supplies of vapor as the cyclone travels sometimes thousands of miles over the surface of the sea toward the British Isles or Iceland.

(13) *The general circulation of a cyclone, as shown by the motion of the clouds, appears to be the same everywhere.*

All over the world unusual coloration of sky at sunrise and sunset is observed not only before the barometer has begun to fall at any place, but before the existence of any depression can be traced in the neighborhood.

Cirrus appears all round the cloud area of a tropical cyclone, instead of only round the front semicircle as in higher latitudes. The allinements (!) *of the stripes of cirrus appear to lie more radially from the center in the Tropics, instead of tangentially to the isobars, as indicated by the researches of Ley and Hildebrandsson in England and Sweden, respectively.*

The general character of the cloud all round the center is more uniform in than out of the Tropics; but still the clouds in rear are always a little harder than those in front.

The broad current of air over the West Indies constituting the "trade wind" reaches from the surface of the sea 4 or 5 miles upward, as is shown by the daily movements of large and well-formed cumuli.

The dividing plane between the upper part of this current and the lower part of the next layer or stratum is strongly marked in Jamaica from May to October. The following account was given by the writer in 1896 in Jamaica Weather Report No. 193:

When rain begins to fall from a large cumulus, a quantity of cloud is poured into the air from the top of the cumulus, as smoke from a factory chimney; this takes place in all parts of the world when rain falls from cumuli, but in the Temperate Zones only a little *false cirrus*, or cirriform cloud, is thrown off. In Jamaica the process is on a gigantic scale, and the cloud is spread out as a sheet far and wide so as to shade the land for some hours from the direct rays of the afternoon sun. It is therefore a common cloud in the west-central district of Jamaica during the summer and autumn months.

Its texture at first is thick and woolly, but as it spreads the sheet becomes thinner; it then generally settles down as stratus, and finally it disappears a little after sunset, leaving the evening sky perfectly clear. As it spreads and settles the typical features of cirro-stratus and alto-stratus may sometimes be seen, but such features are not lasting.

Abercromby in his "Instructions for Observing Clouds"[15] described strato-cirrus as follows:

A cloud identical in general structure with cirro-stratus only denser and at a lower level. * * * The thin flat layer of cloud is drawn out at the edges into fibers, which shows that the cloud is a compound of cirrus and stratus; but as the cloud is dense and comparatively low, we know that it ought to be called strato-cirrus.

Now, this strato-cirrus is formed at great elevations: some measures in Jamaica made it as much as 6 miles; and it forms the dividing plane between the trade-wind current and the higher regions of cirrus. Indeed, it is curious to watch the large cumulo-nimbus moving along from the east-southeast, and the strato-cirrus pouring from the [its] top in a totally different direction; but the absence of cirrus under these really fine-weather conditions makes it impossible to say whether the drift of the strato-cirrus is that of the cirrus or not.

Consequently in the trade-wind current we have stratus and cumulus and all their compounds moving from the east-southeast together with the wind; and above these we have cirrus and cirriform cloud moving from any point of the compass, but from the west as a general average for the West Indies.

Regular observations are made in Jamaica at 7 a. m. (75th M.), but for the proper observation of cirrus the time should be about an hour earlier, or near sunrise; and when a cyclone is approaching a constant watch should be kept until strato-cumulus or other lower clouds begin to cover the sky; but as there is often a fine day with a slight rise in pressure before the approach of a cyclone (sec. 6), as night must often intervene, as lower clouds soon move up and showers begin to fall, and as showers soon pass into rain squalls, there are remarkably few observations of cirrus under cyclonic influence among our notes and records.

Again, as in the case of the wind, we have to select those cyclones which are not interfered with by secondaries or other cyclones at a distance, and we must also know accurately the positions of their centers.

On this account my early work on this subject was considered unsatisfactory, but of course the lower clouds were much the same as the wind; indeed, among the hills the cloud level lowers under cyclonic influences so that the hills are capped with stratus, and the wind and fog move together; as seen from the plains the stratus follows the law of vertical succession. But the cirrus not only moves from the center but even farther around than the Habana observations indicated.[16]

It is here proposed to consider cloud motion under cyclonic influence as observed in the hurricanes of 1903, 1915, and 1916, of which the records and charts are published but to which we may now add a few cloud observations taken at irregular hours.

In the following table, β is the direction in which the center lies from the place of observation measured from east around by north, and r is the distance in miles, both taken from charts; ϕ' is the angle between the observed wind arrow and the center; ϕ is this angle corrected for the constant east-southeast drift; ϕ_1, ϕ_2, ϕ_3 are the angles between the arrows flying with the stratus, cumulus, and cirrus, and the center; in the last column β has been deduced from two or three of the functions, ϕ, ϕ_2, ϕ_3.

15 Ed. Stanford, London, 1888.
16 West Indian Hurricanes, by E. B. Garriott. Washington, 1900. p. 18.
   Relation of the Movements of the High Clouds to Cyclones in the West Indies, by John T. Quin. MONTHLY WEATHER REVIEW, Washington, 1907, 35: 215–219, 510–511; 1909, 37:134–141.

Cloud-drift and the center.

Date.	Hour.	Place.	Center. β	Center. r	Wind. φ'	Wind. φ	Clouds. φ₁	Clouds. φ₂	Clouds. φ₃	β deduced.	Notes.
			°	*Miles*	°	°	°	°	°	°	
1903. Aug. 10	7 a. m.....	Sav-la-mar....	350	550	125	83	....	....	(125)	....	1 cir.¹
10	6 p. m.....	Brandon Hill.	350	315	148	32	....	....	215	358	1 cir.
10	3 p. m....	Vale Royal....	350	180	....	....	....	125	204	342	Str-cum: cir-str. and cir. At Christiana in Manchester cirrus bands were seen to stretch from N. to. S. across the sky about this time.
11	4 a. m.....	.....do........	350	26	35	31	....	125	181	399	Str.-cum: cir-str. and cir.
1915. Aug. 12	7 a. m.....	Morant Point.	345	280	75	65	75	....	....	....	10 str.-nimb.
12	7 a. m.....	Kingston......	346	322	76	50	121	76	211	356	4 cum: 1 cir.
12	11 a. m....	.....do........	348	246	78	58	123	100	213	347	1 cum: 6 cir-str. and cir.
12	3 p. m.....	.....do........	352	183	82	56	127	....	....	....	10 str.-nimb.
12	7 a. m.....	Kempshot....	344	402	74	52	74	....	....	....	10 str.
12	10 a. m....	.....do........	346	345	98	76	98	121	211	333	2 fr.-cum: cir-bands with motion along their length. Thin cir-veil over blue sky.
12	11 a. m....	.....do........	346	326	98	65	121	....	....	....	4 cum.
12	2 p. m.....	.....do........	348	274	....	....	....	123	....	....	Cir-bands NW. and SE. moving from E. across 10 cir-str. Z.
12	5 p. m.....	.....do........	350	222	....	....	....	125	170	358	Scud.
12	3 p. m.....	Negril Point...	351	295	81	59	81	....	....	....	
1915. Sept. 27	11 a. m....	Kempshot....	154	632	19	65	19	....	176	160	Cir-band moving along its length.
1916. Aug. 14	7 a. m.....	.....do........	343	750	163	35	....	....	203	349	5 cir.
14	3 p. m.....	.....do........	343	600	141	25	....	....	208	354	10 cir-str.² Great haze over the land like that over the sky.
15	3 p. m.....	Kingston......	329	62	59	47	59	....	....	....	10 nimb.
15	4 p. m.....	.....do........	324	42	54	28	....	99	....	345	Cum-nimb.
15	5 p. m.....	.....do........	317	22	25	(12)	....	92	....	....	Cum-nimb.³
15	9 p. m.....	.....do........	178	42	43	48	43	....	....	....	Str.
15	6 p. m.....	Kempshot....	327	71	102	78	102	....	....	....	10 str.
15	6 p. m.....	Negril Point...	342	97	72	54	72	....	....	....	10 nimb.
29	6 a. m.....	Kempshot....	338	800	158	81	....	....	203	318	2 cir.
30	6 a. m.....	.....do........	338	340	136	83	136	....	203	323	Cir-band seen among 10 str.
30	11 a. m....	.....do........	347	240	145	49	....	145	189	342	Cir-band moving along its length.
Means...	....	....	....	....	....	56	....	113	199	....	

¹ Some cirriform cloud had apparently settled down to the level of the middle class.
² Probably dense cirrus.
³ Kingston was just at the edge of the central area and the wind, which was only 28 miles, was blowing almost straight in. See section (12).

It will be noticed that with two exceptions the center was always in the east-southeast quadrant; this is of course the most important quadrant for Jamaica, but a more general analysis could have been wished (see Note D).

With regard to cirrus, taking the mean of φ₃ to be 199°, the greatest difference from the mean is 29°, and the average difference is 13°; cirrus is therefore somewhat more reliable than the wind or cumulus.

And when the three—wind, cumulus, and cirrus—or any two of them, are observed, and β deduced and compared with β taken from the charts, it will be found that the greatest difference is 21°, and that the average difference is 10°; so that greater accuracy is obtained when two or three aerial currents are observed, as might have been expected.

There is as much cirrus in the rear of a West Indies cyclone as there is in front; often there is more; and cirrus moves away from the center after it has passed in exactly the same manner as when it approached.

And with reference to the Habana observations, when a cirrus band moves along its length then the direction of the band indicates the position of the center; otherwise the position of the center must be inferred from the motion of a point on a band; and as many of these bands are very uniform, it is often difficult to find a well-marked point.

The present cloud results are in close agreement with those found many years ago, to which reference was made above; and consequently these results may be said to be based on observations extending over 30 or 40 years.

With regard to strongly marked colors in the sky at sunrise and sunset, it were greatly to be wished that they were always to be observed before a cyclone, or before the pressure begins to fall; but this is not the case; sometimes the strongest colors appear in connection with quite small depressions; and sometimes with large cyclones they hardly appear at all.

(14) *Everywhere the rain of a cyclone extends farther in front than in rear. Cyclone rain has a specific character quite different from that of showers or thunderstorms; and this character is more pronounced in tropical than in extratropical cyclones.*

Thunder or lightning are rarely observed in the heart of any cyclone, and their absence is a very bad sign of the weather. Thunderstorms are, however, abundantly developed on the outskirts of tropical hurricanes.

In section 6 reference was made to the daily thunderstorms in the central parts of Jamaica during the autumnal months; and in the last paragraph it was stated that on the approach of a hurricane the hills are capped with clouds, that lower clouds soon cover the sky, and that showers begin to fall which pass into rain squalls; and these are both distinct from our winter "northers," when the steady wind from the north sweeps across the sea and throws down any quantity of rain on the opposing hills on the north side of the island.

So cyclonic rain is very distinct; and while thunderstorms may occur on the outskirts of a hurricane, they are not a feature of our cyclonic weather; and in this way when rain and wind set in during the autumnal months the absence of thunderstorms may be "a very bad sign" to the community at large.

(15) *Squalls are one of the most characteristic features of a tropical cyclone, when they surround the center on all sides; whereas in Great Britain squalls are almost exclusively formed along that portion of the line of the trough which is south of the center and in the right rear of the depression. As, however, we find that the front of a British cyclone tends to form squalls when the intensity is very*

great, the inference seems justifiable that this feature of tropical hurricanes is simply due to their exceptional intensity.

As the central area of a cyclone approaches, the squalls become terrific and apparently it makes no difference on which side of the area the observer may be. In the August hurricane of 1915, the squalls at Kempshot were as bad seven hours after nearest approach as they were an hour and a half after, the center moving away at the rate of 19 miles an hour.

It so happens that a visitor from Ireland in 1815 experienced the Jamaica hurricane in October that year, and wrote a brief note on the subject some years after,[17] in which he refers to the squalls more particularly. The house he was in at Hope Bay gave way, and shelter had to be obtained elsewhere; it was then that "these gusts of wind appeared to roll on like volumes of water, the trees and bushes crashing beneath their pressure, one of these wind waves coming on the heels of another."

(16) *A patch of blue sky in the center of a cyclone, commonly known as the "bull's-eye," is almost universal in the Tropics, and apparently unknown in higher latitudes. This blue patch does not apparently always coincide exactly with the barometric center. The author's researches show that in middle latitudes the formation of a "bull's-eye" does not take place when the motion of translation is rapid, but as this blue space is not observed in British cyclones when they are moving slowly, it would appear that a certain intensity of rotation is necessary to develop this phenomenon.*

Elsewhere, at page 20 of this article, Abercromby wrote:

Lastly in the vortex of the typhoon we find the "bull's-eye," or calm clear spot a few miles in diameter, surrounded on all sides by the fury of the hurricane. Many accounts received agree in saying that light cirri are usually seen over this area, that near land this space is full of birds taking refuge from the terrific surrounding squalls, and that the heat is suffocating. During the passage of the vortex over Manila on the 20th October (1882), the thermometer rose rapidly and the relative humidity decreased to an extent hardly known in the driest months. The universal exclamation was "The air burns."

In the succeeding typhoon, November 4 and 5, no such central heat was observed, but the intensity of the cyclone was much less.

The instrumental observations at Manila on these two occasions are almost unique, but there is no doubt that a clear hot central spot is a normal feature of tropical cyclones. The oppressive heat and great dryness would probably point to the existence of a slight down draft in the core of the cyclone. It is extremely difficult to form a definite conception of such a system of circulation, for there is not the slightest doubt that the main mass of air in the center of a cyclone is rising.

As remarked in section (12), the air rushes into the central area from every point of its limiting circle with a velocity of $v\cos\phi$, producing an ascending volume rather than current, so that the ascensional motion can hardly be observed.

With regard to the great central heat occasionally felt in a hurricane which passed over one of the Lesser Antilles a few years ago, it was reported that at a certain place the people were deluged with "hot water" instead of rain.

The central calm area of the Jamaica hurricane of 1903, August 11, was 10 miles in diameter; the wind in this area was light and variable as to direction; the clouds were light cumuli, with patches of blue sky among them, and they were rotating slowly in the same direction as the hurricane outside the calm area. I did not notice any great increase in temperature.

In the hurricane of 1916, August 15–16, the diameter of the central area was as much as 38 miles, but it was "calm" only in comparison with the hurricane outside. The area, however, did not pass over me.

The following account of the calm area of cyclone B, November 18, 1912, was given in Jamaica Weather Report No. 411, page 4:

The calm central area of cyclone B was as much as 20 miles in diameter, and as it passed over any place toward evening the cloudy sky was lit up by a bright orange glow. Many allusions are made to it among the notes sent me by different correspondents; at Kempshot the calm began at 3 p. m., and at 3:30 p. m. patches of blue sky were seen high up toward the southwest, and also toward the north; later on the clouds had a misty churned-up appearance, but they were high above the ground; at 5:15 p. m. fog came on, or rather the clouds came down to our level of 1,800 feet, and at 5:40 p. m. the fog had an extraordinary orange color, not in any particular direction, but uniformly colored in every direction; at 5:45 p. m. it was exceedingly bright; at 5:55 p. m. the wind recommenced, from northwest with rain, all the color disappeared, the squalls got stronger, and the second hurricane was upon us in full force at 6:35 p. m. Now sunset occurred at 5:14 p. m. standard time of the 75th meridian, the time used recently in Jamaica; so that the color was brighter half an hour after sunset, when also the calm area passed away from Kempshot; so that the color must be connected with the evening colors after sunset and the central calm area. If the latter could be regarded as an enormous cylinder reaching above the dark thick clouds of the surrounding hurricane, its top might easily be so illuminated as to throw the glow down the cylinder and to distribute it uniformly. I am not aware that the appearance has ever been seen before.

On this occasion there was enough "intensity of rotation" to satisfy anyone—120 miles an hour. The wind instruments were destroyed, and this estimate was made from the pressure required to hurl about a terrace a number of heavy *cubical* flower pots, out of which the plants were blown early in the proceedings.

(17) *The trough phenomena—such as a squall, a sudden shift of wind, and change of cloud character and temperature just as the barometer turns to rise, even far from the center—which are such prominent features in British cyclones, have not been even noticed by many meteorologists in the Tropics. The author, however, shows that there are slight indications of these phenomena everywhere, and he has collated their existence and intensity with the velocity of propagation of the whole mass of the cyclone.*

Reference was made in section (1) to the circularity of most of the cyclones which have passed over Jamaica; and, of course, we would hardly expect any "trough phenomena"; but it often happens that near the time of lowest pressure, or when the barometer begins to rise, there is a remarkable drop in pressure and a heavy squall, but without any shift in the wind.[18]

(18) *Every cyclone has a double symmetry. One set of phenomena, such as the oval shape, the general rotation of the wind, the cloud-ring, rain area, and central blue space, are more or less related to a central point. Another set, such as temperature, humidity, the general character of the clouds, certain shifts of wind, and a particular line of squalls, are more or less related to the front and rear of the line of the trough of a cyclone.*

The author's researches show that the first set are strongly marked in the Tropics, where the circulating energy of the air is great and the velocity of propagation small; while the second set are most prominent in extra-tropical cyclones,

¹⁷ A Voyage to Jamaica, by *James Kelly.* Belfast, 1838.

¹⁸ Hurricane of 1916, Oct. 12, see Jamaica Weather Report No. 462, p. 5, footnote; Hurricane of 1916, Nov. 8, see Jamaica Weather Report No. 464, p. 4.

where the rotational energy is moderate and the transitional velocity great.

The first set of characteristics may conveniently be classed together as the rotational; the second set as the translational phenomena of a cyclone.

(19) *Tropical and extra-tropical cyclones are identical in general character, but differ in certain details, due to latitude, surrounding pressure, and to the relative intensity of rotation and translation.*

MOTION OF TRANSLATION AND ROTATION.

According to section (11) it might be imagined that a cyclone consisted of a number of spiral rings of wind rotating more and more rapidly as they approached the center, while the whole mass of air moved onward.
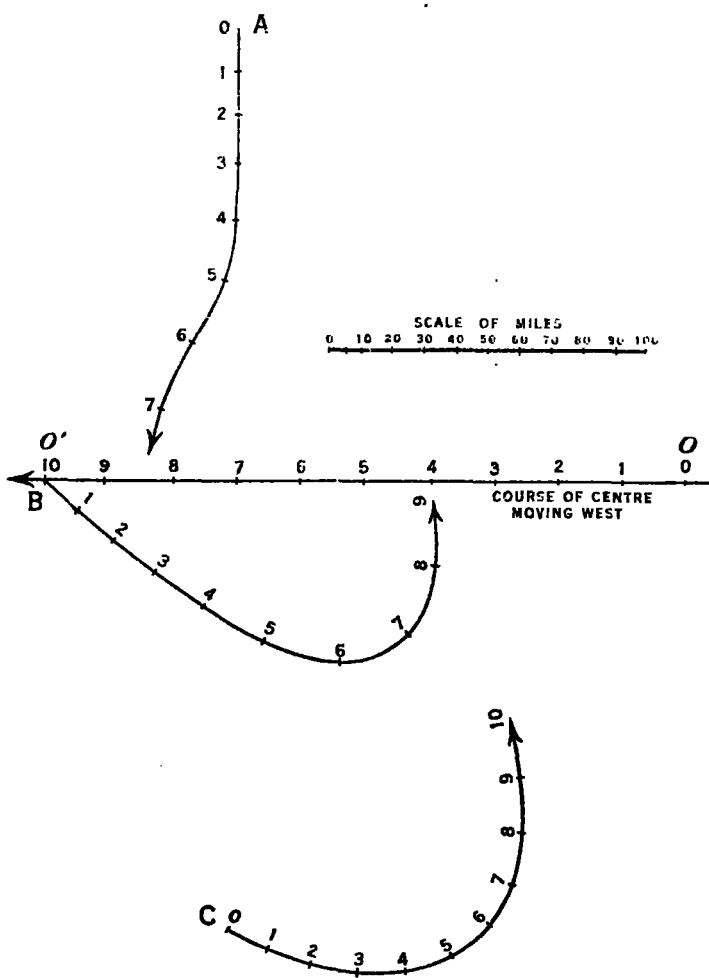

FIG. 9.—Tracks of portions of air at A, B, and C, relative to the center moving from O to O'.

Consequently if the cyclone were moving toward the west the wind at a point north of the center would be moving with its rotational velocity *plus V*, the velocity of translation of the center; and the point at the same distance south of the center would be moving with the same rotational velocity *minus V;* and when *V* is large, say 20 miles an hour, the effect on the wind north and south of the center will be strongly marked. And of course every point on a spiral would be affected one way or another.

Such a system does not represent a cyclone at all. Sir Napier Shaw, F. R. S., director of the British Meteorolo-

gical Office, has shown that if each portion of air within a cyclone simply moves at any instant in accordance with its position and distance from the center at that instant, then the effect of the motion of the center is to make the air sweep in from the north to the central line and then sharply turn round the center, or even get caught by the hurricane ring surrounding the calm central area; while the air south of the central line hardly approaches, or even moves away from the center.

In figure 9 let us consider the three points A, B, C, in front of an advancing cyclone whose center is O, all at the distance of 200 miles from the center; at A the center lies to the southeast, at B to the east, and at C to the northeast.

The fall of pressure corresponding with r must be taken from equation (1), in which we shall take $a=0, c=2$; then v is known from equation (4); and the direction of motion for each quadrant is given in the table in section (11).

Take V, the velocity of the center, to be 20 miles an hour; and then we can roughly draw the lines and curves in figure 9, showing the positions of the center and of A, B, and C, from each hour from 0 to 10.

It will be seen that A is drawn into the hurricane ring round the center, that B, moves round the center and that C after describing a short curve is left behind.

Generally speaking, in figure 9 we see that the faster the motion of the center, the faster the air north and south of the central line changes its direction, while the velocity depends on r, the distance from the center, and its functions Δp and G.

Now, while the center moves forward, the oval isobars also move forward, not by pushing the air in front but by a wavelike transmission of pressure; and thus from moment to moment the whole cyclone may be imagined to take up fresh positions along its line of advance without any part of the air being moved by that advance.

Consequently, when the central area passes over a place where there is no gradient and no wind due to cyclonic rotation, there is also no wind due to cyclonic translation, although the cyclone may be moving at the rate of 20 miles an hour.

The effect of passing into the central area, from hurricane to fine weather in the course of a few minutes, is always surprising; and the damage done must always cause anxiety as to the coming hurricane when passing out.

APPLICATION OF RESULTS TO ACTUAL CYCLONES.

In "The Observer's Handbood," issued annually by the Meteorological Office, London, or in "Hints to Meteorological Observers,"[19] will be found full information respecting meteorological instruments and their management, and a great deal of valuable information, so I shall only remark that mercurial barometers should be used instead of the more convenient aneroids, for the simple reason that the latter soon get out of order; moreover they have to be continually compared with a mercurial standard, as absolute pressures are required.

Good mercurial barometers are necessary in dealing with cyclones at a distance and small depressions near at hand; they must be read to the nearest 0.002 inch, and the usual four reductions to standards of temperature, elevation, gravity, and Kew for instrumental error, must be made.[20] Again the readings must be corrected for di-

[19] W. Marriott, Ed. Stanford, London.
[20] The United States Weather Bureau groups these four under the two heads "Instrumental error" and "altitude" corrections. The mercurial barometer is read to 0.001 inch.—C. A., jr.

urnal variation of pressure which goes on regularly hour after hour, storm or no storm, for this variation is as large as the fall due to the distant disturbances we want to measure. After these corrections the third decimal figure can not of course be depended on, but it should be retained until the reduced reading has been subtracted from the average pressure for the time of the year, and the fall below mean obtained, and then the third figure should be rejected.

With regard to wind instruments, Robinson's anemometer is most valuable in giving the average velocity for short intervals of time; and it is to these velocities that our formulæ always refer. It can also be used in checking estimated velocities during a considerable length of time; but when the velocity is very great and the gusts tremendous, it seems doubtful whether any instrument [in general meteorological use] can measure them correctly.

For daily registration of cloud observations in the Tropics there should be three columns headed "lower," "middle," and "upper," for stratus, cumulus, and cirrus; and when the cloud forms become mixed as a storm comes on, it may at least be possible to refer them to their proper columns. But fracto-stratus and fracto-cumulus are sometimes very much alike when driven before a rising gale; and either dense strato-cumulus or dense cirriform cloud forms the overhead canopy.

With regard to cirrus and cirro-stratus, the observers in Jamaica, including myself, have generally confined cirrus to its definition: "Detached clouds of delicate or fibrous appearance often showing a feather-like structure" etc. Consequently we have applied cirro-stratus to include dense cirriform sheets; but the definition of cirro-stratus is: "A thin whitish sheet of cloud" etc., and I am inclined to think that the latter definition should be preserved, noting "dense cirrus" when necessary; "cirrus bands" forming a connecting link between the two forms.

In this case cirro-stratus will be seen for a short time only; and the sequence for an advancing cyclone will be: cirrus according to definition, cirrus-veil, cirro-stratus, cirrus bands, and dense cirrus. But of course stratus, or strato-cumulus, prevents, as a rule, any such complete sequence from being observed.

We shall now consider a few cases.

EXAMPLE 1.

August, 1915, Kempshot. Mean barometer, 29.928 inches.

Ins.
9th 7 a. m., 29.978⎫
9th 3 p. m.,　.997⎪

10th 7 a. m.,　.976⎬Fine weather; usual winds and clouds.
10th 3 p. m.,　.967⎪

11th 7 a. m.,　.942⎭
11th 3 p. m.,　.888, very fine, calm, clear.
11th 7 p. m.,　.859, very fine clear evening.

12th 7 a. m.,　.788, wind, north, 15 miles an hour; 10/10 str., north.

It was now apparent that there was a cyclone to the east, and the large fall between 7 a.m. on the 11th and 7 a.m. on the 12th indicated that it was moving westward on the southern or middle track (see fig. 4). The stratus blowing over the hilltop prevented any observation of the upper clouds.

At 10 a. m., however, the stratus broke up, and the following were the notes made:

Aug. 12, 1915. 10 a. m.

Ins.
29.749 nne, 20 mis./hr.　2/10 Str., nne.
　　　　　　　　　　　　2/10 Fr-Cu., ne.
　　　　　　　　　　　　1/10 Ci. band, se.
　　　　　　　　　　　　Thin cirrus veil over blue sky between clouds.

Now from the parallelogram of velocities (fig. 7) it was found that the cyclonic wind was 21 miles from the north, so that a was 270°, and so that

From the wind.. β=314°
From the cumulus... β=338°
From the cirrus... β=334°

Mean.. β=329°

The true value of β was 346°, so that the deduced direction of the center was fairly correct.

It will be noticed that the wind velocity was in accordance with the fall below mean, namely, 0.18. In fact, between 7 a. m. and 1 p. m., the observed wind was 15, and the cyclonic wind 17, which is in exact accordance with equation (4). But after 2 p. m. irregularity set in: the wind died down; sometimes there were puffs from the west: and all the time the barometer was steadily falling. The irregularity was due to a secondary in advance of the primary on its northwest edge; and nothing more could be made of the wind.[21]

The barometer was falling steadily, however, and might indicate whether the center was approaching Kempshot directly or not.

Let V be the velocity of the center in miles per hour, and G be the gradient in inches of mercury per mile; then the rate of fall per hour will clearly be GV, provided that the center is moving toward the place of observation.

But $G = \Delta p/2r$ from equation (2) supposing that $a = 0$; and as the time of arrival is clearly r/v, provided again that the center is moving toward the place of observation, it follows that

$$\text{Time of arrival} = \frac{\text{Fall below mean}}{\text{Twice rate of fall}}. \qquad (6)$$

It is important to show that this equation requires no computation; the barometer readings must of course be reduced and corrected for diurnal variation, and then arranged as in the following table, where the difference of pressure between 7 p. m. and 9 p. m. is twice the fall per hour, and is set opposite 8 p. m., and the rest follows as a matter of course:

Date and hour.	Barometer.	Fall below mean.	Twice rate of fall.	Time of arrival.
	Inches.			
Aug. 12, 1915, 7 p. m..............	29.673	0.26	....	....
8 p. m..............	.646	0.28	0.055	13th, 1 a. m.
9 p. m..............	.618	0.31	0.055	2:30 a. m.
10 p. m..............	.591	0.34	0.048	5 a. m.
11 p. m..............	.570	0.36	0.031	11 a. m.
12 p. m..............	.560	0.37	....	

The want of constancy in the last column clearly showed that the center was passing by Kempshot, either to the north or south of that place.

There is not much more of interest; rain squalls set in at 11 p. m. when the center was 113 miles away; after 1 a. m. on the 13th the heavy northwest rain squalls showed that the center was passing north of Kempshot; the lowest pressure was 29.286 inches at 5:25 a. m. with wind south, 40 to 60 miles an hour with the usual heavy squalls; and the nearest approach of the edge of the calm area was 25 miles.

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[21] The confusion reached a climax at 7 p. m. when some lower cloud was moving fast from northeast, and when there were some cirrus bands also moving from northeast.

EXAMPLE 2.

August. 1916, Kempshot.   *Mean barometer, 29.920 inches.*

10th, 7 a. m., 29.970
11th, 7 a. m., 30.053
12th, 7 a. m., 30.047   Fine weather; usual winds and clouds.
13th, 7 a. m., 30.007   On the 10th and 11th usual showers from cumuli.
13th, 3 p. m., 29.982
14th, 7 a. m., 29.921   Wind east 5 mis./hr.; 5/10 cir., sc. Fine.
14th, 3 p. m., 29.897   Wind eastnortheast 3 mis./hr.; 10/10 cir.-st., se.[22]
                    Great haze over the land.

The anemometer showed an average of 8 miles an hour between 7 a. m. and 3 p. m., and this was used to find the cyclonic wind which was 6 miles from the north, so that a was again 270°; and

From the wind.. $\beta = 314°$
From the cirrus.. $\beta = 334°$

Mean.. $\beta = 324°$

while the true β from the subsequent chart was 343°.

15th, 7 a. m., 29.803 inches: wind light and variable, 5/10 A.-Cu., ne., 5/10 cirrus veil.
15th, 3 p. m., 29.721 inches: wind, ne., 20 mis./hr., 4/10 Fr.-Cu. ne., 6/10 St.-Cu., ne.

Consequently the cyclonic wind, $v = 18\frac{1}{2}$, which is in almost exact agreement with equation (4); and $a = 248°$; while

From the wind... $\beta = 292°$
From the St.-Cu... $\beta = 338°$

Mean.. $\beta = 315°$

and the true β was 322°.

At 6 p. m. the usual rain squalls set in, and equation (6) was applied; but as the center again was not directly approaching Kempshot, it will be convenient to apply equation (6) to Negril Point Lighthouse observations, with the following results:

Date and hour.	Barometer.	Fall below mean.	Twice rate of fall.	Time of arrival.
1916. Aug. 15, 6 p. m.	*Inches.* 29.641	0.28		10 p. m.
7 p. m.	.574	0.35	0.112	10 p. m.
8 p. m.	.529	0.39	0.196	10 p. m.
9 p. m.	.378	0.54	0.286	11 p. m.
10 p. m.	.243	0.68		

As a matter of fact the edge of the calm area arrived at 11 p. m. It passed centrally over Negril Point Lighthouse, and subsequently the wind rose to 96 miles, and even to 120 miles an hour for short intervals, as measured by the anemometer.

Returning to Kempshot: The lowest pressure was 29.19 inches; the wind was estimated at 60 miles an hour, and equation (4) gives 64. But the gusts were very heavy; the pressure plate showed a maximum of "30 pounds" per square foot; and if

$$v^2 = 280P, \tag{7}$$

then for the particular instruments at Kempshot, the maximum gust was 92 miles an hour, or half as much again as the average wind.

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[22] Dense, and therefore to be taken as cirrus.

NOTES.

(A) *The gradient:*

Let Δp be the fall below mean at a point on the curve r miles from the central area; let $\Delta p'$ be the fall when r is increased by 1. Then if G be the gradient,

$$G = \Delta p - \Delta p' = \Delta p (1 - \Delta p'/\Delta p),$$

$$= \Delta p \left\{ 1 - \left(\frac{r-a}{r-a+1} \right)^{\frac{1}{2}} \right\},$$

$$= \Delta p \left\{ 1 - 1 / \left(1 + \frac{1}{r-a} \right)^{\frac{1}{2}} \right\},$$

$$= \Delta p / 2(r-a), \text{ nearly.}$$

(B) *The tangent:*

Let Δp_0 be the fall at the center, let Δp_1 be the fall at the point where the tangent takes off, and let r_1 be the distance of this point from the central area. Then

$$G = \Delta p_1 / 2(r_1 - a) = (\Delta p_0 - \Delta p_1)/r_1,$$

therefore

$$r_1 \Delta p_1 = 2(r_1 - a)(\Delta p_0 - \Delta p_1),$$

therefore

$$(r_1 - a)\Delta p_1 = 2(r_1 - a)(\Delta p_0 - \Delta p_1 - a\Delta p_1),$$

therefore

$$\Delta p_1 = 2(\Delta p_0 - \Delta p_1) - a\Delta p_1/(r_1 - a),$$
$$= 2/3\Delta p_0 - a\Delta p_1/(3[r_1 - a]).$$

But from equation (1)

$$p_1^2 = c^2/(r_1 - a);$$

and eliminating $(r_1 - a)$,

$$\Delta p_1 = 2/3\Delta p_0 - a\Delta p_1^3/3c^2.$$

(C) *The constant k:*

Let $t = 0°$, so that $p = k\rho_0$, where ρ_0 is the density of the air at 0° corresponding to the pressure p. But if B_0 be the height of the barometer reduced to 0° at the place where the experiment was made to determine k, g be the force of gravity at that place, and σ_0 the density of mercury at 0°, then

$$p = g\sigma_0 B_0 = k\rho_0,$$

so that

$$k = g\frac{\sigma_0}{\rho_0}B_0.$$

And by taking feet and seconds as the units of space and time, and by weighing equal volumes of mercury and of air at pressure B_0, k was found equal to 843,663. To reduce feet per second to miles per hour we must multiply by 15/22; but k must be multiplied by the square of this ratio, remembering that g is given in feet per second per second; and so we get $k = 392,200$ in miles per hour.

(D) A few values of ϕ_2 and ϕ_3 were found for $a = 39°$, and 189°, so that we have the following:

β	ϕ_2	ϕ_3
343°	113°	199°
39°	105°	198°
189°	69°	189°

We notice failure for ϕ_2 when the center lies to the west. This is quite in accordance with the breaking up of the clouds, all but the highest, after a cyclone has passed; but while the center is more or less to the east, the direction of cumulus can be depended on as already stated, though preference should be given to cirrus.